INFLUENCE OF A FLUID LUNAR CORE ON THE MOON S ORIENTATION. J. G. Williams, D. H. Boggs, J. T. Ratcliff, C. F. Yoder and J. O. Dickey, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail James.Williams@jpl.nasa.gov)).

Introduction: A molten lunar core will affect the Moon's rotation through two torques. A fluid core, rotating independently from the solid mantle, has a velocity difference at the core-mantle interface. The velocity difference causes a force, dissipates energy, and leads to a net torque over the whole surface. If the core-mantle boundary is oblate, there will be a second force due to flow along a nonspherical boundary. This torque depends on the orientation of the core spin vector with respect to the mantle pole. The two torques have different directions and their influences on the rotation are distinguishable in principle. The Lunar Laser Ranging (LLR) data are sensitive to variations in lunar orientation and rotation rate.

Precession: The mantle equator plane tilts 1.54 deg to the ecliptic plane and it precesses with the same 18.6 yr period as the orbit plane precesses along the ecliptic. The fluid core also precesses, but the expected tilt to the ecliptic is only a few arc minutes. The mantle and core precessions are forced, and their tilts and nodes are functions of lunar physical parameters.

The model for precession consists of a solid mantle and an independently rotating fluid core. A solid inner core is not considered, but is not excluded by the data. The torque on the mantle which forces precession depends on the whole Moon (C-A), where A<B<C are the principle axis moments of inertia. Part of that torque is transmitted to the core through dissipative coupling at the core-mantle interface (parameterized with K) and the core principle moment difference (C'-A'), where A'<C'. The forced precession of the core due to the two torques is nonlinear in the parameters K/A' and core dynamical oblateness (C'-A')/A'. The observable response of the mantle to the precessing core depends on K/C and (C'-A')/C. In the first approximation the combinations (C'-A')/A'and (C'-A')/C determine the (in-phase) components of core and mantle orientation, respectively, aligned with the orbit tilt. Dissipation combinations K/A' and K/C determine the orthogonal (out-of-phase) components for core and mantle orientation, respectively, in the first approximation. Since it is the motion of the solid Moon which is measurable in the Lunar Laser Ranging analysis, the determined quantities are K/C and the product of core dynamical oblateness and core/mantle moment ratio.

The model and theory for core dissipation and tides are developed in [1]. That model is implemented in the numerical integration of lunar rotation. It was concluded from fits [1,2,3] that the Moon has a small liquid core. Application of Yoder's turbulent boundary layer theory [4,5] indicates a core radius <352 km if molten iron and <374 km for the Fe-FeS eutectic. Core oblateness is not considered in that model or the associated fits.

The in-phase tilt of the solid Moon depends on (C-A)/C, Love number k_2, and two third-degree gravitational harmonics in addition to (C'-A')/C. Core flattening can affect the determination of k_2 as argued in [6].

Fits: New fits include a free parameter for tilt angle as a preliminary way to allow for core oblateness. The tilt correction is weakly determined, about 1.3 times its uncertainty. The resonant free core nutation period would be roughly 1/2 to several centuries, consistent with the estimate of [7]. In these solutions the Love number k_2 is 0.025, with uncertainty 0.003, 12% less than spherical core models. A concordant spacecraft determination of the lunar Love number is 0.026 with uncertainty 0.003 using variation of the gravity field [8].

The LLR detection of core oblateness is not strong, but the shift in the Love number is noteworthy. If a spherical core is assumed then the fit Love number is larger and the associated uncertainty is much smaller than the above [1,6]. The Love number is a function of the S-wave speed in the Moon and may be compared [6] with the seismic results [9,10]. This comparison is complicated by the sparse distribution of deep ray paths in the Apollo seismic measurements. The deep seismic speeds are not well determined. As shown in [6], even with a fluid core the deep S-wave speeds would have to decrease to match the LLR Love number using a spherical core. Allowing for core oblateness makes this comparison more comfortable.

Summary: Core oblateness and dissipation effects are present for a liquid core, but not for a completely solid core. The dissipation determination is strong, but is complicated by the need to separate solid-body tidal and core dissipation. The core oblateness can provide a check on the liquid state of the core (a solid inner core is not excluded). While the observational evidence for core oblateness is presently weak, solutions for core oblateness and Love number are consistent with other knowledge of lunar properties. Additional accurate laser ranges should improve the solutions.

References: [1] Williams J. G. et al. (2000) submitted. [2] Williams J. G. et al. (1998) *Abstracts LPSC XXIX*, Abstract No. 1963. [3] Williams J. G. et al. (1999) *Abstracts LPSC XXX*, Abstract No. 1984. [4] Yoder C. F. (1981) *Phil. Trans. R. Soc. London A*, *303*, 327-338. [5] Yoder C. F. (1995) *Icarus, 117*, 250-286. [6] Dickey J. O. et al. (1994) *Science*, *265*, 482-490. [7] Petrova N. and Gusev A. (2000) in press. [8] Konopliv A. S. et al. (2000) submitted. [9] Goins N. R. et al. (1981) *J. Geophys. Res.*, *86*, 5061-5074. [10] Nakamura Y. (1983) *J. Geophys. Res.*, *88*, 677-686.